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APPLICATION NUMBER: *60/505,024*
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S/N 60/505,024 **PATENT**

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In re Applicant: Menachem BARAK
Serial No.: 60/505,024
Filed: September 24, 2003

REQUEST TO CORRECT SPELLING OF INVENTOR'S NAME

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

Applicant respectfully requests that the spelling of the name of the inventor currently named as "Menachem Barak" in the above-referenced patent application be corrected to read "Menashe Barak"

The United States Patent and Trademark Office is hereby authorized to charge Deposit Account 501380 in any other amount necessary for the fulfillment of this request.

Respectfully submitted,

Daniel J. Swirsky
Agent for Applicant
Registration No. 45,148

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60/505024 U.S. PTO 092403

PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

INVENTOR(S)

Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
MENACHEM	BARAK	HAIFA, ISRAEL

☐ *Additional inventors are being named on the ___ separately numbered sheets attached hereto*

TITLE OF THE INVENTION (280 characters max)

A PULSE MODULATOR WITH PULSE SHAPING AND
PULSE EXTINGUISHING FOR FLASHLAMP ANNEALING

Direct all correspondence to: **CORRESPONDENCE ADDRESS**

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ENCLOSED APPLICATION PARTS (check all that apply)

☒ Specification *Number of Pages* 27
☒ Drawing(s) *Number of Sheets* 12
☐ Application Data Sheet. See 37 CFR 1.76
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METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT

☒ Applicant claims small entity status. See 37 CFR 1.27.
☐ A check or money order is enclosed to cover the filing fees
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☒ No.
☐ Yes, the name of the U.S. Government agency and the Government contract number are: ______________

Respectfully submitted,

SIGNATURE ____________ Date 9/24/03

TYPED or PRINTED NAME DANIEL J. SWIRSKY

REGISTRATION NO. (if appropriate) 45,148

Docket Number: 1244-USP

TELEPHONE 011-972-2-999-1035

USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

A Pulse modulator with Pulse Shaping and Puls Extinguishing for Flashlamp Annealing

Background of the Invention

1. Field of the Invention

This invention relates generally to tools and processes that heat a workpiece by directing thermal radiation towards it and optionally spreading that thermal radiation in a uniform manner by some optical means. More particularly, it relates to a method and apparatus for producing an intense flash of electromagnetic radiation which lasts for about 50 to 5000 microseconds. The workpiece in this particular case may be a silicon wafer of diameter of 300 mm. A silicon wafer is subjected to many different processes before a complete semiconductor device is realized on the device side of the wafer, which acts as a substrate. One particular family of processes related to this invention is known as Rapid Thermal Processing (RTP). More particular relation of this invention is to a group of processing techniques within the RTP family known as Flash Annealing, which is conducted with either a laser, and designated as Laser Thermal Annealing (LTA), or with flashlamps and designated as Flashlamp Annealing (FLA).

2. Related Art

Many applications require heating or annealing of an object or a workpiece. For example, in the manufacture of semiconductor chips such as microprocessors and other chips, a semiconductor wafer such as a silicon wafer is subjected to an ion implantation process, which introduces impurity atoms or dopants into a surface region of a device side of a wafer. The ion implantation process damages the crystal lattice structure of the surface

region of the wafer, and leaves the implanted dopant atoms in interstitial sites where they are electrically inactive. In order to move the dopant atoms into substitutional sites in the lattice to render them electrically active, and to repair the damage to the crystal lattice structure that occurs during ion implantation, it is necessary to anneal the surface region of the device side of the wafer by heating it to a high temperature, generally more than 1000 degrees Celsius.

However, the high temperatures required to anneal the device side also tend to produce undesirable effects using existing technologies. For example, diffusion of the dopant atoms deeper into the silicon wafer tends to occur at much higher rates at high temperatures, with most of the diffusion occurring within close proximity to the high annealing temperature required to activate the dopants. As performance demands of semiconductor wafers increase and device sizes decrease, it is necessary to produce increasingly shallow and abruptly defined junctions, and therefore, diffusion depths that would have been considered negligible in the past or that are tolerable today will be unacceptable in the next few years and thereafter. The only way to achieve these goals is to heat the surface region of the device side of the wafer- called the front surface of the wafer hereafter, faster and faster, with dwell time at peak temperature that approaches zero, and then let it cool as fast as possible. The time history of the surface temperature is called in the art by different names, trying to visualize the faster and steeper heating and cooling: pulse, spike, impulse, and recently flash RTP for annealing are the most wide spread, with flash being the fastest and steepest of them all.

Flashlamps and lasers thermal pulse generators, as ultra-fast annealing tools for semiconductor wafers, were discovered, invented, and researched in the mid and late seventies, but were abandoned by tool makers in the mid eighties because the technological demands did not justify their development. Recently however, both sources were "rediscovered", and are extensively researched and developed as candidate technologies for near and far future tools for ultra rapid thermal annealing (RTA) – also called Flash Annealing, Laser Thermal Annealing (LTA), or Flashlamp Annealing (FLA), forming ultra-shallow junctions (USJ), with sharp profiles of dopants concentration, high activation levels, and without significant diffusion of dopants. In the case of flashlamps, this is accomplished by storing electrical energy in capacitors prior to ignition, and then igniting all the lamps simultaneously. The ignition is electronically similar to closing a high

voltage gas filled switch – the flashlamp – which then connects an ohmic load – again the flashlamp itself – to the stored energy, thus generating an electrical pulse. The apparatus which contains the stored energy and the closing switch is generally termed a pulse modulator or pulse generator. The apparatus that charges the capacitors with a high DC voltage is generally termed a charging power supply, and is not part of the present invention. The ignition of the flashlamps, which is also not part of the present invention, converts a small part of the gas inside the lamps to electrical conducting plasma, which is able to start discharging the stored electrical energy through each and every one of the flashlamps. The discharge converts very fast most of the gas inside the flashlamps to plasma, raising its effective core temperature to 6000 -16000 degrees Kelvin, depending on amount of discharged energy and the type of gas inside the flashlamp, with only a very thin and "cold" sheath of gas adjacent to the inner surface of the quartz envelope of the flashlamp. About 40-50% of the stored electrical energy is emitted as light in the UV-Visible-Infrared spectrum (0.2 – 2. microns wavelength) through the transparent quartz envelope of the flashlamp. This light is a form of electromagnetic radiation which may be absorbed in a workpiece facing it, raising its temperature in due course, or otherwise illuminating a volume or activating some chemical or biological reaction due to the high percentage of ultra violet and visible light in the emitted radiant flash. The whole process from ignition to the end of the electrical pulse and the accompanying light flash may last from 50 – 5000 microseconds, depending on the electrical design of the modulator and the ability of the flashlamps to withstand short flashes. Low power flashlamps can produce flashes whose width is shorter than 50 microseconds, even approaching 100 nanoseconds and less.

Among other things, high power lasers and flashlamps differ in the nature of their light: very narrow spectral bandwidth in lasers, compared to very broad spectrum in flashlamps, coherent light in lasers, non coherent light in flashlamps, the shortest flash duration possible: a few tens of nanoseconds in lasers as compared to a few tens of microseconds in flashlamps, and in the available radiant power. Lasers are energy limited to a beam diameter of a few tens of millimeters, and thus are designed for the dimensions of a single die (chip area) on the front side of a wafer. The beam must be scanned across the wafer's device side, following the patterns on the wafer in a complex and time consuming manner which limits drastically the throughput of the RTA tool. On the other hand, the energy in a

single laser flash is enough to raise the front surface of the die's area from room temperature to the limit of the melting temperature of silicon (about 1400 C) without any prior heating. Flashlamps in contrast to lasers can be bundled together in an appropriate optical manner, to cover the whole device side of a wafer of 300mm diameter in a single flash. On the other hand, raising the whole front surface of the wafer in a single flash, from room temperature to 1400 C, will dictate a large amount of flashlamps, causing mutual shadowing inside the light collecting optics, with fast deterioration of efficiency, compactness, and simplicity. A compromise of preheating the whole bulk of the wafer to an initial temperature of about 400 – 700 C by additional hardware, prior to initiation of the flash, achieves a significant reduction of the number of flashlamps needed. With an initial wafer's bulk temperature of 400 C for example, about 200 – 300 kilojoules of electrical energy, stored in capacitors, are needed in order to raise the surface to 1400 degrees C. This dictates about 5 – 10 meters overall length of flashlamps of a large diameter such as 15 to 21 millimeters, which are cut to as many as 20 or more distinct flashlamps in order to fit them efficiently in an appropriate optical system. Optimizing and controlling the discharge of such an amount of stored energy by an efficient and as small as possible pulse modulator and its accompanying bank of flashlamps, is mandatory.

Since the front side of the wafer contains layers and structures of many derivatives of silicon like oxides and nitrides, optimal peak temperature of the flash annealing process should be controlled very accurately, and with only a small margin below actual melting. Current FLA process peak front surface temperatures are 1150 – 1350 Celsius with dwell time in the region of the peak temperature preferably minimized to zero. Overshoot or inaccuracies of the peak front surface temperature are strictly forbidden. Any proposed technology for flash annealing should thus preferably contain means to extinguish the flash as fast as possible upon reaching a preset set point, forcing an immediate cooldown with zero overshoot in peak temperature.

There are quite a few patents which propose mechanical and optical means to collect the light flash from a single or multiple flashlamps in an efficient manner and then to distribute this light very uniformly on the front side of a silicon wafer, as well as preheating the bulk of that silicon wafer to an initial temperature from behind. Such examples are US patents no. 4571486, 4649262, 4698486, and 6594446. While the uniform distribution of the flash

across the front face of the wafer and the adequate uniform bulk preheating are important prerequisites for flash annealing, none of the above mentioned patents give adequate solutions to other important issues regarding the power electronics of the flashlamps and which are addressed in the present invention, namely: optimizing the shape of the flash curve with time, and then shutting off the flash instantly when reaching a certain set point.

One particular solution which does address these issues partially is disclosed in International Publication Number WO 03/060447. In the '447' publication, the modulator topology proposed is the simplistic series LC circuit which is the least optimal topology for a pulse modulator for flash annealing, and does not lend itself to any shaping of the flash profile, as will be explained in detail below. Manipulating the pulse width of the flash and its shape is very limited and partial, accompanied by a dangerous alteration of the necessary impedance matching between the modulator (source) and the flashlamps (load) during the pulse itself, and a considerable overshoot of the flash during termination, due to a large amount of residual energy still flowing into the load after termination. The inventors thus claim only the ability to control the total (integral) power to the load in response to a command. Moreover, the above mentioned partial power control is achieved by semiconductor switches of the Thyristor (SCR) type, which are limited by voltage and current to low power flashlamps only. Indeed the power of the flash in the '447' publication is modest, and is compensated by a very powerful and fast pre-heater, providing an initial bulk temperature of about 700 – 900 degrees C prior to flashing.

Another proposed system for flash annealing is disclosed in International Publication Number WO 03/009350. In the '350' publication, the proposed topology of the modulator is of the least optimal series LC variety, and no shaping or triggered termination of the pulse is possible.

Japanese Patent Application JP2003007632 discloses an idea of using an independent distinct pulse modulator for each and every of the many flashlamps in the system, igniting and discharging them in a sequence, such that only a partial number of lamps is working concurrently at the same time. No shut off of the flash is done electronically, only the stopping of the cascade of ignitions, but flash and temperature overshoot are supposed to

be smaller since only low power lamps at a controlled number are used. Standard non optimal series LC topology is utilized.

Accordingly, there is a need for better ways to design pulse modulators for Flash Lamp Annealing (FLA) with improved electrical topologies and methodologies capable of shaping the flash temporal form optimally, and with controllable self extinguishing capabilities, resulting zero overshoot of the heating process to the workpiece and accurate repeatable peak annealing temperatures. The present invention advantageously addresses the above needs.

Summary of the Invention

The present invention provides a high power apparatus or pulse modulator, and a method for generating a fast pulse of high energy and controlled duration (width) into a load such as a flashlamp. The resulting pulse contains two distinct characteristics. The first characteristic is a unique temporal shape of the pulse which results in an increase in the electrical power delivered to the load towards the end of the pulse just before fall time commences. This pulse shaping is advantageous for applications such as flashlamp annealing (FLA) of the front (active) side of a silicon wafer. The amount of shaping or increase in the electrical pulse power at the late part of the pulse is controlled beforehand by the operator, and is achieved with no alteration of the characteristic output impedance of the modulator, which should be matched to that of the load such as a bank of flashlamps. With regard to the second characteristic of the resulting pulse, the present invention utilizes a unique methodology which positions a plurality of standard high voltage and current triggered closing switches, such as triggered spark gaps or pseudosparks, at specific key points within the pulse modulator. The Multiple Switch Array (MSA) comprised of the plurality of the triggered closing switches, is positioned and interconnected in such a way as to control the width of the electrical pulse to the load, by rerouting the power flow from the load to other dissipative receivers, such as power resistors, upon receiving a single electronic trigger command common to all the switches comprising the MSA. Furthermore, the termination of the pulse in the load is executed by the multi switch array

(MSA) in a very sharp and well behaved manner, producing neither an overshoot nor a zero gradient point in the power to the load following the termination command. This type of flash extinguishing is mandatory for applications such as flashlamp annealing of the front (active) side of a silicon wafer. Moreover, the methodology of the present invention, using an MSA to reroute the excess capacitive and inductive energy, still stored in various parts of the modulator, to ohmic resistances other than the load, prevents any hazardous reversal of voltages or oscillations in the storage capacitors of the modulator. The pulse modulator and the MSA within it are not limited by the level of the charging voltage, the maximum pulse current, or the level of ignition pulse potential needed for the flashlamps.

In accordance with a first aspect of the invention, a modified topology for a pulse modulator is presented, one which can store very large amount of electrical energy at a level of up to tens of thousands of volts, and then discharge that energy through multiple flashlamps by initiation of an appropriate ignition pulse. Commencing the lamps ignition, the proposed modulator produces an electrical pulse which is more appropriate to the needs of present and future flash thermal annealing processes than any other prior art modulators or power supplies, because it produces on the front side of the workpiece, on account of the distinctive temporal shape of the resulting electrical pulse, steeper heating and cooling rates and higher peak front surface temperatures, given the same initial conditions and same components count and denominations as competing prior art systems. These two parameters: higher peak temperature and steeper temperature profile with time, are very important for elimination of dopants thermal diffusion into the bulk of a silicon wafer, for achieving a high degree of activation of the dopants in the lattice, and for elimination of mechanical dislocations, cracks, or even a complete failure due to the severe thermal stresses induced in the silicon wafer, and which are maximal at the front surface. Moreover, the boost in peak temperature and the sharpness of the temperature time history is achieved in a passive way, inherent to the topology of the circuit, and governed by the mutual magnetic coupling chosen between the various inductors existing in the circuit. The resulting output impedance of the pulse modulator remains constant and unchanged during the whole electric pulse, which is very important for the efficient delivery of energy to the load. Source (modulator) and load (flashlamp) should have matched impedances for best overall efficiency and sharpest temporal form of the front surface temperature that can be achieved.

In accordance with a second aspect of the invention, the termination or extinguishing of the flash can be controlled, in a very abrupt manner and with an initiation accuracy of a microsecond, such that any additional electrical energy remaining in the system after the command for termination, residual or substantial, capacitive or inductive, will be redirected to dissipative electrical loads other than the flashlamps, resulting zero overshoot in the flash. Such a precise control over the flash duration is responsible for tighter thermal process parameters, no overshoot in temperature of the front side of the active layer of a wafer, and very good repeatability of the process parameters among many wafers. The apparatus which implements such a precise control over the flash duration, called a MSA and described in greater detail below, uses standard off the shelf components such as spark gap or pseudospark type closing switches, which are not limited to certain levels of voltages, currents, or energies, and are not limited to any amount of installed flashlamps or storage capacitors. Most importantly, the methodology of the present invention for the electrical connections of the MSA within the pulse modulator of the present invention, suppresses successfully any harmful or dangerous side effects as a result of the MSA closing, such as over voltages, over currents, and especially reversed voltages of more than 15%, at any point or node of the proposed pulse modulator.

These and other features and advantages of the present invention will be more readily apparent from the detailed description of the preferred embodiments set forth below taken in conjunction with the accompanying drawings.

Brief Description of the Drawings

The accompanying drawings, which are incorporated into and form a part of the specification, illustrate several embodiments of the present invention and, together with the description, serve to explain the principles of the invention. The drawings are only for the purpose of illustrating preferred embodiments of the invention and are not to be construed as limiting the invention. In the drawings:

Fig.1 shows an electrical schematic of prior art embodiment of a pulse modulator for general electrical loads including flashlamps.

Fig.2 shows graphical results of computer simulations conducted on some examples of the prior art pulse modulator of fig.1.

Fig.3 shows the resulting front surface temperatures developed in a 300mm silicon wafer, as a result of the various electrical discharges presented in fig.2 (prior art).

Fig.4 shows an electrical schematic of the preferred embodiment of the present invention for utilizing a pulse modulator with pulse shaping for general electrical loads including flashlamps.

Fig.5 shows an equivalent electrical network schematic of the preferred embodiment of a pulse modulator in the case of a PFN of order n = 2 + 2.

Fig.6 shows the degree of power shaping achieved by the preferred embodiment of fig.4 for various values of the order n+n and the mutual coupling coefficient k.

Fig.7 shows the resulting front surface temperatures developed in a 300mm silicon wafer, as a result of the various electrical discharges of the preferred embodiment of the pulse modulator of fig.4, as given in fig.6.

Fig.8 is an electrical schematic of the preferred embodiment of the present invention for a proper methodology to extinguish the flash and to achieve a variable pulse width with classic pulse modulators of prior art as in fig.1.

Fig.8A is an electrical schematic of the preferred embodiment of the present invention for a proper methodology to extinguish the flash and to achieve a variable pulse width with the preferred embodiment of the present invention for a pulse modulator as in fig.4.

Fig.9 shows simulation results of surface temperature on a 300 mm wafer flashed with the preferred embodiment of a pulse modulator while activating different switches to achieve pulse extinguishing.

Fig.10 shows the effect of choosing different values of R_c on the resulting front surface temperatures developed in a 300mm silicon wafer with the preferred embodiment of the present invention for variable pulse width.

Fig.11 shows the resulting voltage reversal developed by the preferred embodiment for flash extinguishing, for different switches locations and values of R_c.

Detailed Description of the Invention

Referring to Fig.1, a typical prior art pulse modulator **10** is shown. It contains n capacitors **13a** to **13n** conveniently but not necessarily of equal capacitance, and n inductors **14a** to **14n**, conveniently but not necessarily of equal inductance. The integer n can be of any practical value. If n=1, system **10** is designated as: Series L-C circuit; If n=2–20 the circuit is called: Pulse Forming Network (PFN) of order n or LC Ladder Network with n sections. In the limit when n is very large, it is generally called Pulse Forming Line (PFL). The total energy stored in the circuit (for equal C) is:

$$J = 0.5\, n\, C\, V_0^2 \qquad \text{[Joule]} \qquad (1)$$

Where V_0 is the charging voltage, supplied by an appropriate DC high voltage power supply **16**, through a current limiting resistor **15** of high resistance. A high voltage / high current switch **7**, a switch closing trigger mechanism **17** and a load **8** of total ohmic resistance R_t are connected to the PFN output ports **9** and **6**. By closing switch **7** through the appropriate command to trigger mechanism **17**, a pulse of electric current through load resistor **8** is initiated. It is important to note that switch **7** must be able to withstand the full charging voltage V_0. One or more flashlamps **11** in series can replace switch **7** and load **8** as shown in fig.1. Since a flashlamp behaves as a good electrical insulator prior to its ignition and as a resistor of a low ohmic value R_t after ignition, it is clear that flashlamp **11** replaces both the switch **7** and the load **8**. The trigger mechanism of a flashlamp is called igniter and is designated as **29** in fig.1. It is generally connected to metal wires **12** which are wrapped around the exterior tubing of flashlamps **11**, forming a small high voltage capacitor with the positive anode electrode and the negative cathode electrode of each flashlamp. A high voltage pulse of 10 to 40 kilovolts is created by igniter **29**, and is coupled electrically by the small wire capacitor **12** to the strong electric field which exists between the flashlamp electrodes, due to charging voltage V_0. The high ignition voltage pulse causes a strong distortion of electric field inside the flashlamp, and consequently a

breakdown of the gas inside the flashlamp and the subsequent creation of electrically conducting plasma inside the flashlamp. This and other variants of igniter **29** are well known in the art and are explained in details by W. R. Hook et al in IEEE Transactions on Electron Devices, Vol. ED-19, No. 3, pp. 308-314,1972. Once the load (**8** or **11**) is electrically connected to the output port (**9, 6**) of pulse modulator **10** the initial voltage V_0 in capacitors **13a-13n** starts discharging into the load into adjacent capacitors of lesser instantaneous voltage, through the various inductors **14a-14n** until all voltages in system **10** diminish to zero.

The task of inductances **14** is to limit circuit currents, once discharge commences, and to "stretch" the time duration of the discharge to a desired value, without dissipating energy (contrary to what the resistive load does). It is possible to have mutual magnetic coupling between the various inductors, due to their mechanical proximity to each other, such that one coil is in the magnetic field created by another coil. If this is the case, additional mutual inductances exist and should be taken into consideration. For example in fig.1 are designated 3 different mutual couplings as **21**, **22**, and **23**. Mutual coupling between coils has a magnitude and also a polarity, designated by a small dot on one side of each coil in fig.1. The specific dots in fig.1 designate the correct polarity for a good quality flash. A PFN of order n, as per fig.1, with equal coefficient of mutual inductance k and same polarity between each and every inductor, with equal inductors L_0 and with equal capacitors C in all its n sections, is generally known in the art as Guillemin type E network and is the easiest to analyze analytically.

Assuming for convenience equal L_0 and M, the coefficient of mutual coupling k will be of value: $k = M / L_0$ for all the n sections of the PFN in fig.1. Inductance L_0, capacitance C and coefficient k determine the time ~~duration (10%-90%) T of the electrical~~ discharge by:

$$T = 2\,n\,[\,(1+2k)\,L_0\,C\,]^{0.5} \qquad [\text{sec}] \qquad (2)$$

The characteristic impedance of the PFN is:

$$Z = [\,(1+2k)\,L_0\,/\,C\,]^{0.5} \qquad [\text{ohm}] \qquad (3)$$

The resistance of the flashlamps, once ignited, is small (of the order of a few ohms or less). The actual instantaneous resistance of a flashlamp is given approximately by the semi empirical formula:

$$R_t = K_0 / I^{0.5} \ \text{[ohm]} \ ; \quad K_0 = C_1 L_t / D_t \ [\text{ohm} - A^{0.5}] \qquad (4)$$

K_0 is called the lamp impedance parameter, I is the instantaneous varying current through the lamp, L_t is the active length of the flashlamps: the summation of all the distances between the electrodes of all the flashlamps in series, D_t is the inside diameter of the quartz tubing of the flashlamp, and C_1 is a constant which depends on the type of filling gas and its filling pressure, being about 1.28 for Xenon at 450 Torr. Because only the total electrical length of the flashlamp L_t appears in equation (4), regardless of the actual mechanical division to a number of distinct flashlamps with separate envelopes, as long as they are connected electrically in series, we will adopt the notation of drawing a single resistive load of value R_t.

The average resistance of the load R_t during the high current middle portion of the pulse, weather it be a single flashlamp, a series of flashlamps, or any other electrical load, should be matched by proper design to the characteristic impedance Z of the circuit as calculated by equation (3). This is important for high efficiency in transferring most of the stored energy in the capacitors to the load. If $R_t > Z$, time duration T increases above what equation (2) predicts and the pulse variation with time becomes unsymmetrical, with a longer fall time. If $R_t < Z$, oscillations commence with decay time longer than what equation (2) predicts. Equation (2) is the minimum value possible for T and is strictly true only when $Z = R_t$. Since Z is constant but R_t may be varying in time because of the term $I^{0.5}$ in equation (4), or any other characteristic of the load, impedance matching is a "cut and try" situation.

As n increases, the rise and fall times of the current pulse shorten, and the current pulse form approaches a square or a trapezoid with some ripples in the mid section of the pulse. When n = 1, the form of the current pulse resembles a trigonometric function. A square like flash form will be advantageous to thermal heating or annealing but up to a point: the high voltage pulse capacitors needed for the job are very large, heavy and expensive, auxiliary components for controlling the flash shut off increase accordingly, and the actual influence

on the temperature versus time curve diminishes as n increases. Thus, for optimal size and cost, the logical choice for the case of producing a high power light flash to heat a workpiece in a FLA process is n = 2 - 3.

Fig.2 shows results of computer calculations for the electrical power dissipated in a flashlamp during a single pulse, performed on system **10** of fig.1. All cases shown in fig.2 as well as in all the other figures showing computer simulation results and attached to the present invention, use equal C, L_0, and k and have the same data base: Flashlamp impedance parameter K_0 = 76 ohm-$A^{0.5}$; Charging voltage V_0 = 15000 Volt; C = 235 uf; L_0 = 180 uH; Total installed capacitance = 2/n*235 microfarad; Total installed inductance = 2/n*180 microhenry. Impedance matching is evident from the symmetrical rise and fall times of all the five cases in fig.2, as well as the influence of raising n from 1 to 2 and 3 with regards to making the pulse squarer. Parameter k has a large influence on the ripple and symmetry in the middle part of the pulse.

Fig.3 shows results of heat conduction calculations on a 300mm silicon wafer at an initial bulk temperature of 400 degrees Celsius, performed with the electrical power for a single lamp from fig.2 as input to 4 lamps connected to 4 identical pulse modulators as of fig.1, together with some logical assumptions on electrical, radiant, geometrical and optical efficiencies, totaling together an overall electrical to heat radiation efficiency of 0.16, and an effective front surface emissivity of 0.5. All thermal and optical properties of silicon were taken from the literature, as well as the approximate spectrum of commercial Xenon flashlamp light. For reasons of clarity, fig.3 shows only the peak surface temperature and its vicinity. It is easy to note the different peak process temperatures, the rate of heating before the peak and rate of cooling by conduction into the depth of the substrate during the fall time of the pulse. High heating and cooling rates are very important not only for a good annealing process as explained above, but also for immunity against possible cracks and mechanical failure due to thermal stresses which develop in the wafer during the flash and cool down and which are maximal at the front surface as disclosed by G. G. Bentini et al in Journal of Applied Physics, Vol. 54, No. 4, pp. 2057-2062, 1983. The higher the temperature is the steeper temperature gradient with time is the better, weather in heating or in cooling. In fact, unless temperature rise and fall times are fast enough, the workpiece is susceptible to serious damage due to thermal stresses. It is a known fact that

the yield stress of silicon and many other crystalline materials increases with increasing strain rate of deformation, while at the same time decreases exponentially with temperature. Rate of change of strain is directly proportional to rate of change of temperature. When checking for thermal stress failure in various flash situations, It is important to take into consideration both elastic and plastic strain and to use the "apparent" and not the real Young modulus, as teaches us T. Fukuda in Japanese Journal of Applied Physics, Vol. 35, part 1, No. 6A, pp. 3209-3215, 1995. Thus, reaching the peak temperature, where the time derivative of temperature there is zero, as is clearly seen in fig.3, is dangerous and should be avoided. One possible remedy is to extinguish the flash automatically before the peak is reached. It is also noted in fig.3 that the case of n=2, k=0.3, gives a better temperature temporal shape for an FLA process than does the case n=3, k=0.3. Varying k is very easy, but increasing n costs a lot of money, volume and weight.

A very recent compilation of 14 different pulse modulators and with a comprehensive list of references is disclosed by Geun-Hie Rim et al, in IEEE Transactions on Plasma Science, Vol. 31, No. 2, pp. 196-200, 2003. None of the circuits cited in that reference is optimal for our needs because in the case of flash heating, the flatness (minimum ripples) of the mid section of the pulse, which is what most designers are trying to achieve, is not important, on the contrary: a significant increase in current, like a secondary pulse imposed on the main pulse, at the end of the pulse just before fall time, will be much more advantageous. This conclusion is reached by comparing fig. 2 and fig.3 and realizing that the surface temperature of the workpiece is increasing even during the ripples in the middle part of the pulse, and that the peak temperature is reached during the first quarter to third of the fall time. The preferred embodiment of the present invention for a pulse modulator, which produces this pronounced secondary increase in current just before the beginning of the fall time, is described in fig.4 by a system **30**. It is important to note that while it is convenient to calculate the performance of any PFN using equal inductors L_0 and equal capacitors C, it is not mandatory. The preferred embodiments of the present invention are presented in this manner of equal L_0 and equal C, and the computer simulations were conducted accordingly, but the present invention is equally valid with varying and different capacitors and inductors.

System **30** in fig. 4 introduces a new PFN (pulse forming network) designated as order n = j+j, j has an optimal value of 2-3 for flash annealing. These are two ordinary PFNs of order n each, but connected electrically back to back at node **31n**, sharing a common ground node **36** and serve two similar loads **11** on each side. Each half of system **30** is comprised of n capacitors **13a-13n** and n inductors **14a-14n**. Each half is connected to one effective load such as a flashlamp **11**, so that its average ohmic resistance R_t is a good match to the circuit impedance Z, which remains unchanged as per equation (3). If more flashlamps are needed for heating, no additional flashlamps are added in series, but instead multiple systems **30** should be incorporated in a single pulse modulator, since impedance matching is essential. It should be emphasized that due to the special symmetric structure of system **30**, only an even number of flashlamps is possible. Most important and crucial to the present invention is the fact that the connection between the two ordinary PFNs at node **31n** is accompanied by an appreciable amount of magnetic coupling M, imposed between the two adjacent inductors **14n** on both sides of symmetry node **31n**, and designated as **39**, the correct polarity of which is dictated by the dots **28**. The 2n coils needed for implementation of system **30** may be distinct and separated coils, or they can be fabricated from a single coil with taps. Since the currents, circulating in the circuit in the case of flash annealing of a 300mm wafer, may reach many thousands of amperes, the various coils **14a-14n** in system **30** can't be mutually coupled by a common ferrite or powdered iron cores, due to saturation. Only air core coils should be used. The only possibility to achieve the needed mutual magnetic coupling with air coil cores is by the proper mechanical and geometrical structure of the coils. The most adequate form is that of a single coil assembly, designated as **42** in fig.4. To illustrate the preferred embodiment of a single coil assembly **42**, all coils **14a-14n** are drawn as they are actually built mechanically according to the preferred embodiment: a single layer coil assembly, of a single uniform diameter and pitch of winding, with two ends **26** and **27**, one common center tap **31n**, and two rows of n-1 taps **31a**, **31b**, up to **31n-1** on each side of center tap **31n**. All the taps are symmetrically and uniformly distributed across the windings on both sides of center tap **31n** to form 2n inductors. Weather the various coils in system **30** are constructed from distinct inductors or from a single coil assembly **42**, the dots **28** signify the proper polarity of the mutual magnetic coupling needed between the various coils in the preferred embodiment. If the single coil assembly is wound as described above, the proper polarity of the mutual coupling results automatically in a simple and easy manner.

Created by the specific mutual magnetic coupling designated by dots **28**, are 3(n-1)2+3 additional inductors of mutual inductance M. If all self inductances in system **30** are equal and of value L_0 Henry each and all coefficients of mutual magnetic coupling between adjacent coils are also equal to each other and of equal value k each, the following relation holds:

$$M = k L_0 \tag{5}$$

If the preferred geometry of a single coil assembly **42** with equally spaced taps is used in system **30**, the size of k, M, and L_0 are uniquely determined by any three independent dimensions of the single coil e.g.: its diameter, its total length, and the diameter of the cable used for making the coil, or: its perimeter, total number of turns, and total length.

A trio of mutual inductances of size M each: two of positive sign and one of negative sign, are created at each tap **31a-31n**. To understand more precisely the formation of these additional mutual inductances, an electrical equivalent of the network between ports **26** and **27** of system **30** for the case n = 2+2 and with all C **(13)**, L **(14)**, and k equal, is given by network **40** in fig.5. As shown, three additional effective mutual inductors appear at each tap **31, 32, 33**; Two of +M Henry **(34)** and one of -M Henry **(35)**. It is to be understood by anyone of an ordinary skill in the art that neither L nor M need be identical across the network **40**. For example the pitch of winding or the coil diameter could be varied from center to edge to render different self and mutual inductances at different taps of the coil, although symmetry with respect to the centerline **31-36** as well as keeping the same direction of the windings, as indicated by the polarity of mutual inductances **34** and **35** in network **40**, is very important. Coefficient k should be chosen between 0.15 and 0.4, ~~and~~ more preferably between 0.23 and 0.33.

It should be noted that without the magnetic coupling between the two symmetric halves of system **30** or **40**, across the plane of symmetry passing through points **31** (or **31n**) and **36**, we actually cancel only the three mutual inductances **34** and **35** at the center node of symmetry **31** as seen clearly in the schematic of network **40** in fig.5. The two trios of mutual inductances at nodes **32** and **33** of fig.5 may remain as in the prior art of fig.1. The cancellation of the mutual magnetic coupling between adjacent inductors at node **31** is

enough to uncouple the two halves of system **40** (and **30**) electrically and to transfer system **40** back to a prior art standard PFN of order n=2 even though the two halves are still connected electrically together at nodes **31** and **36**. Magnetic uncoupling, with subsequent deterioration of performance (as exemplified in fig.7), may be unintentionally accomplished by lowering the effective k below a value of approximately 0.1. This may happen by miscalculating k through inappropriate mathematical formulae for its dependency on the coil geometry.

Also indicated in fig.4 are two igniters **29**, which on command effectively convert the flashlamps **11** from non conductors to electrical conductors with an effective resistance R_t each. If the load is of a more general case than a flashlamp, igniters **29** should be replaced by two switches in place of each connecting cable **25**. Once loads **11** are effectively connected electrically to modulator **30** at its two outputs **26** and **27**, with their common return port **36**, capacitors **13a** most adjacent to the loads **11**, start conducting their charge through inductors **14a**. Most high voltage high current closing switches, being of a semiconductor type or of a gas filled spark gap type, of which a flashlamp is a special case as described, are of the latching type, meaning that it is impossible to open the switch and cut off or interrupt the electrical currents now flowing in the various loops of system **30** and through all capacitors **13**, inductors **14** and loads **11**, until all voltages in modulator **30** will diminish from their initial value V_0 to zero, by dissipative joule heating in the electrical resistances of the loads **11**, or any other electrical resistance existing in the system, weather of a stray nature like in the various interconnecting metal cables, the inductors and capacitors, or those which will be introduced deliberately for controlling the pulse width, as will be explained below.

Fig.6 and fig.7 show results of computer simulations conducted on the preferred embodiment of a pulse modulator as illustrated in fig.4 and explained in detail above. The same data base was used as for prior art simulations illustrated in fig.2 and fig.3. Fig.6 shows clearly the creation of the pronounced increase (boost) in current and power towards the end of the flash, which is an important part of the present invention, with n=2 and k=0.3 as optimal. Other combinations not shown, such as n=3 with k=0.2 give similar optimal results. Performance above k=0.35 deteriorates rapidly. Fig. 7 shows the simulation results of the front surface temperature development in time, as a result of

connecting 4 lamps to 2 systems **30** with the same data base as before. The increase in peak temperature, rise time, and also fall time of the temperature is pronounced, with n=2+2 and k=0.3 a best combination. Also illustrated in fig.7 is the best temperature curve of the prior art (n=2, k=0.3), copied from fig.3 for easy comparison. The improvement achieved with the present invention is noticeable.

Regarding the second important aspect of the present invention, it is actually a new methodology for terminating or extinguishing the pulse to the load, which has the unique advantage of all the following characteristics simultaneously: (a) termination of the pulse can be executed at any chosen time; (b) termination is very sharp and does not contain any overshoot in electrical power to the load or in the resulting surface temperature on the workpiece; (c) termination is immediate and does not contain any delay in time; (d) termination does not impose any hazardous voltage or current on any component in the pulse modulator, a prohibitive reversal of voltage on part of the capacitors being the most common one; (e) termination can be executed by a simple electrical command such as issued by a comparator, which compares in real time the actual surface temperature with a peak temperature set point. Characteristics (b) and (c) above cause a sudden inversion from heating mode to cooling on the front surface of the workpiece with a sharp peak in surface temperature, provided that cooling did not started before termination, due to the natural decay of the pulse. Cooling by conduction into the depth of the substrate commences when conduction flux is larger than radiation flux by the flash into the front surface.

Referring first to fig.8, it shows system **50** which is the prior art system **10** of order n as presented in fig.1, with the addition of n+1 closing switches SW_0-SW_n, designated in fig.8 as **70**, **71**, **72**, **73**, etc. up to **75** for the nth section. The proposed methodology for extinguishing the pulse is equally efficient and robust in any prior art pulse modulator, as well as in the preferred embodiment of the present invention for a pulse modulator, as was described above with relation to fig.4. Thus, fig.8A shows system **60**, which is the preferred system **30** of fig.4, for the specific example of order n=2+2, with a single coil assembly **42**. Due to the mirror symmetry of the preferred embodiment for a pulse modulator, the preferred embodiment of the proposed methodology for extinguishing the pulse in this case, analogically comprises pairs of switches SW_0 (**70**) and SW_1 (**71**), but a

single switch SW_2 **(72)** at the plane of symmetry. The law in the proposed methodology for extinguishing the pulse in any pulse modulator topology and technology is: a closing switch **70** across each and every load **11** connected to the system, and optionally a switch (**71**, **72**, **73**, and so on up to **75** at the nth section), across each and every storage capacitor **13** in the system. Each of the closing switches in systems **50** and **60** of fig. 8 and 8A respectively, has in series its own current limiting resistor **54** of a small denomination R_c such as 0.5-10 ohm, and of high current capability, not necessarily equal in all places. Switch **71** SW_1 is the only switch that appears in prior art methodologies for power control. All other switches, especially SW_0 **70** across each load, are new and unique to the preferred embodiment of the present invention. It is advantageous, both electrically and mechanically to group all the switches needed to implement the new methodology into a single sub-system called a Multi Switch Array (MSA), which is also triggered by a single triggering system. Output node **9** in fig.8 or symmetrical nodes **26** and **27** in fig.8A, where new switches SW_0 **(70)** are connected, are sometimes susceptible to high voltage spikes during ignition, which can cause false triggering or destruction of the switch. Capacitor **62**, of small denomination such as 1-4 nanofarad for example, and a high permeability ferrite cored inductor **61** of a value 100-200 microhenry for example, solve the problem: they form a high impedance network to the ignition potential, blocking it from reaching the switch **70**, but without choking the ignition potential by overload. On the other hand, when switch **70** SW_0 closes, the large current, flowing from node **26** or **27** to ground **36** through switch **70** and coil **61**, saturates the ferrite core of coil **61** and lowers its effective inductance to a fraction of a microhenry. Capacitor **62** is charged to the same charging voltage V_0 as all other capacitors in the system.

Fig.9 shows the effect of closing either SW_0 (new art), or switch SW_1 (prior art), only one at a time, on the surface temperature of a 300mm wafer. Activation is at the same time = 750 microseconds in all cases, which is the time when the current in the load (flashlamp) **11** is at its maximum. The same database used to calculate all previous results was also used here. The definite conclusion from fig.9 is that the only feasible solution to extinguish the flash instantly and to eliminate any overshoot and peak temperature inaccuracies is the one in which switch **70** - SW_0, the most adjacent to the load **11** is closed. In all the other cases illustrated in fig.9, the residual inductive and / or electrical energy, stored in that part of the pulse modulator which is between the activated switch and the load, is large enough

to maintain additional uncontrolled temperature rise. Also the shape of the peak surface temperature resulting from the new methodology of closing switch **70** SW_0 is the most suitable for flash annealing process due to its sharpness. weather a single switch **70** for prior art pulse modulators, or a pair of switches **70** in the case of a pulse modulator of the present invention, SW_0 **70** can be any switch of a latching or non latching type, capable of sustaining the charging voltage V_0 and the current which will flow to ground through the switch and resistor **54** after termination. Raising the value R_c lowers the current, lowers the reversal of voltage on the various capacitors but also the rate of cooling by conduction into the bulk of the substrate. It should be chosen as the maximal value which still gives adequate cooling curve at the approximate designated termination time. Various cooling curves versus R_c at two different times are shown in fig. 10. Semiconductor switches of the SCR (Thyristor) type may be used with appropriate restrictions on voltage and current as per manufacturer's data. Connecting SCRs in series or parallel to increase voltage or current is problematic and should be avoided. A better choice for high voltage and current applications is the triggered park gap switch. Many feasible candidates are distributed for example by Richardson Electronics Ltd., of LaFox, Il, USA. Another good option is the triggered pseudospark discharge switch, with many models manufactured for example by Pulsed Technology Ltd., of Ryazan, Russia.

Switch **70** SW_0, across each output port of the pulse modulator, guarantees immediate extinguishing of the flash with no overshoot in surface temperature, but it may cause a damaging reversal of voltage across part or all the capacitors in the system. This must be checked and prevented. The preferred embodiment of the present invention solves this problem by closing simultaneously not only SW_0, but also SW_n, SW_{n-1}, and so on, up to and including SW_1, so that no capacitor in the system will be subjected to reversal of voltage. For the same database used in this patent all along, fig.11 shows the location and amount of the maximum reversal of voltage for different combinations of simultaneous switches closing according to the preferred embodiment. Early time of termination time was chosen, such that quite a lot of energy still remains in the various capacitors. As seen clearly from fig.11, the new methodology of the present invention to close switch SW_0 for efficient pulse extinguishing, and to close simultaneously an switches (SW_1 – SW_n) for lowering effects of voltage reversal, can always be tuned, by choosing the value of R_c such that the maximum allowed voltage reversal on C_n will not be surpassed, C_n being the one

subjected to the highest voltage reversal. Lowering R_c can sometimes save the amount of switches needed, on account of higher current through the remaining switches, but fig.11 clearly shows that for best overall results, independent of the value Rc of resistors **54**, all switches SW_1-SW_n, across all capacitors **13** in the pulse modulator, should be closed simultaneously with output port switch SW_0. They all form electrically and optionally mechanically, a single entity called a Multi Switch Array (MSA). It should be noted that the jitter resulting between actual closing the various switches is not critical - a jitter of a few microseconds, which is easily achieved by all the different closing switches referenced above, is quite satisfactory, because SW_0 is the only one to control actual extinguishing of the pulse, all the other switches just lower voltage reversal which evolves over a considerable amount of time span.

CLAIMS

We claim:

1. A new topology for a pulse modulator comprising of :
   a) Two distinct classical PFNs (pulse forming networks) of capacitive and inductive components totaling n sections each (order of n), the various sections not necessarily but preferably equal to each other, with or without magnetic coupling between adjacent sections of each stand alone PFN. Each classical PFN has one output port for connecting an appropriate load, preferebly with matching impedance.
   b) Connecting electrically the two distinct and separated classical PFNs of (a) above, symmetrically back to back (mirror like), resulting a double PFN designated as n+n, with two output ports, each port preserving the electrical characteristic of the classical parent PFN.
   c) Coupling the two PFNs magnetically across the line of symmetry where they are connected electrically back to back. Magnetic coupling can be achieved by different means such as positioning the coils in close proximity to each other or preferably fabricating the 2n coils necessary for utilization of the n+n topology of claim **1(b)** above, from a single coil with (2n-1) taps additional to its two ends. The magnetic coupling between the two back to back PFNs of **1(b)** above alters the shape of the resulting pulse at each one of the two output ports, without otherwise changing the characteristic impedance of the output ports. The amount and polarity of said magnetic coupling controls the form and size of the resulting pulse shaping, and can be optimized for different applications.
2. The topology of claim **1** comprising a mutual magnetic coupling of the same polarity between each and every one of the 2n inductors existing in the n+n topology of claim **1**. Such a single polarity resulting, but is not limited, to the single coil with taps described in claim **1(c)**, provided that the direction of winding is kept the same along its total length.
3. The topology of claim **2** where the coefficient of mutual coupling between each and every pair of adjacent coils or between each and every segment of the preferred

embodiment of a single coil with taps, is constant, preferably of a size between 0.15 and 0.35, and more particularly between 0.2 and 0.3.

4. A system incorporating claim **2**, and preferebly claim **3**, into a pulse modulator, by adding an appropriate charging power supply to charge and store electrical energy in the 2n capacitors comprising the n+n topology of claim **1**, and by the addition of two closing switches, connected to the two output ports of the system, each in series with an appropriate load. Triggering of the two switches simultaneously results a current pulse with a unique temporal shape through each of the two loads.
5. The pulse modulator of claim **4** where the two closing switches in series with the two electrical loads, at the two output ports of the modulator, are replaced by two flashlamps, one at each output port of the two ports of the system. A flashlamp is electrically equivalent to a closing switch with a significant internal resistance, acting as the load. Igniting the flashlamp is equivalent to closing the switch.
6. Single or multiple pulse modulators of claim **5**, each connected to two flashlamps or to two banks of multiple flashlamps in series each, incorporated into the appropriate hardware for flashlamp annealing (FLA) of the front active side of silicon (or other materials of interest) wafers. Such a system has the following advantages over prior art systems with the same amount of stored energy:
   a) Will provide a more intense pulse from the system.
   b) Will provide a more optimally shaped pulse without degrading the impedance matching between modulator (source) and flashlamp (load).
   c) The unique shaping of the pulse results higher and steeper temperature rise (heating) and fall (cooling) on the front surface of the workpiece (wafer).
7. A method to re-route the electrical discharge from the lamps to alternative passive resistors, following a control command, such that :
   a) The delay between the control command and a real decrease of the emitted radiation from the flashlamps is less than 1 microsecond.
   b) The decrease in the emitted radiation flux following the control command will be more than 70% with respect to the flux prior to activation.
   c) The action of re-routing the electrical discharge will **not** introduce:
      I. A reversed voltage on any capacitor in the system, of more than 10%, which is well within the specifications of most capacitors.

II. A surge current greater than the maximum allowed current in any capacitor in the system.

III. An over voltage, in any point in the circuit, above the design charging voltage.

d) The charging voltage of the proposed system can be as high as 30 kilovolts, much higher than the capabilities of semiconductor components, in order to accommodate all sorts of flashlamps and to conserve weight and volume at very high energy levels of hundreds of kilojoules.

e) The method comprised of connecting across each output port of a pulse modulator of arbitrary topology, a closing switch in series with a resistor of low denomination. Both closing switch and series resistor are capable of handling the voltage and current existing prior and after closing the switch.

8. The method of claim 7 with the addition that part or all the capacitors in the pulse modulator used, are paralleled with the switch–resistor series combination of claim 7(e). Moreover, all the switches needed are closed simultaneously by using a single common trigger.

9. A system comprising a pulse modulator such as but not limited to that of claim 4 or 5, and additionally implementing the method of claims 7 or 8 in this modulator, by installing an appropriate switch or Multi Switch Array, chosen from the various available families of semiconductor (SCR, IGBT, or FET), gas filled spark gap, pseudospark or Thyratron switches, according to the voltages and currents which exist in the system, and also installing the appropriate resistors in series with each and every switch.

10. A system of claim 9, where the specific load is a bank of flashlamps and the switches across the loads, as needed according to claim 7(e), are protected from high ignition potentials and interference, resulting false triggering or self break down of the switches, by a ferrite core coil in series with the switch, and a capacitor in parallel with the switch. The coil is designed to have a high inductance before closing of the switch, and a complete saturation after closing the switch.

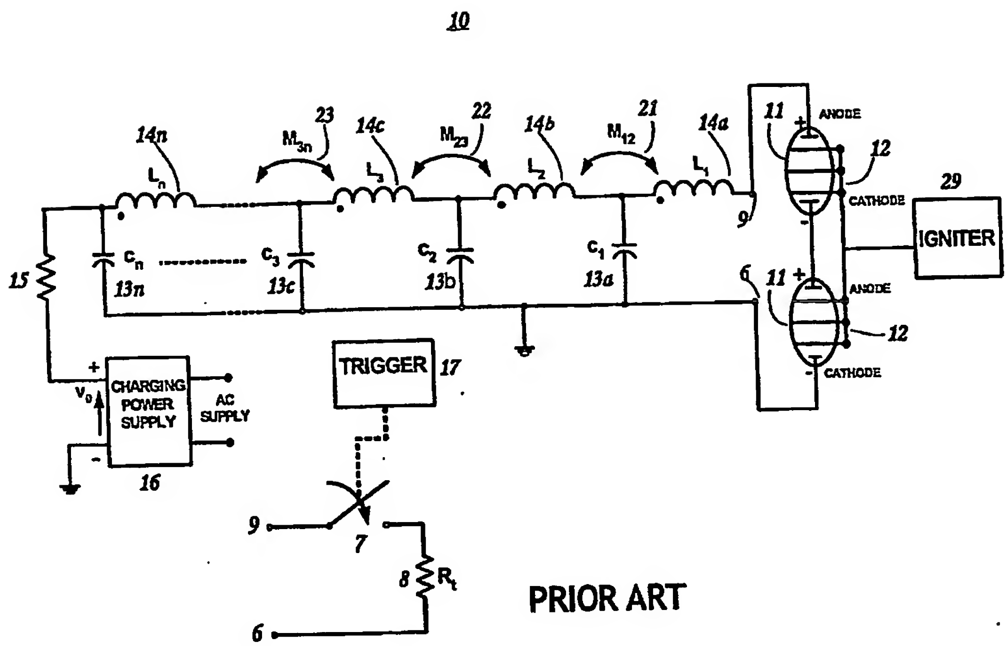
11. A system of claim 10 incorporated into the appropriate hardware for flashlamp annealing (FLA) of the front active side of silicon (or other materials of interest) wafers. Such a system has the following advantages over prior art systems with the same amount of stored energy and same flashlamps:

a) Will provide an exact extinguishing of the flash with no overshoot in surface temperature of the workpiece.
b) Will provide a more abrupt turn around from heating to cooling with no point of zero temperature temporal gradient.
c) Can be triggered easily into extinguishing by actual surface temperature measurement to form a closed loop control on surface temperature.

Abstract

A pulse modulator is disclosed which can drive any load but is particularly attractive for multiple discharge lamps, also called flashlamps, connected as a load, in order to produce flashes of light which can heat, irradiate, or illuminate a surface or a workpiece such as a silicon wafer. The bank of flashlamps may include as few as 2 lamps to as many lamps as needed without any constraint except that the overall number of flashlamps should be an even number. The modulator incorporates a new topology for the electrical circuit, which produces a distinctive temporal shaping of the pulse, resulting in a current boost towards the end of the pulse. This current boost achieves accordingly an improved shaping of the surface temperature versus time profile, which is characterized by a higher and steeper temperature peak: a shape which is optimal for thermal flashlamp annealing (FLA) of ultra shallow junctions (USJ) on the front (active) side of a silicon wafer. The improvement in the shape of the temperature variation with time is compared with other prior art systems using the same type and number of lamps, same amount of installed storage capacitance, and same amount of stored electrical energy. A second important aspect of the proposed pulse modulator is its ability to terminate very sharply the pulse of electric power into the load and thus to practically extinguish the flash of light, very abruptly and at any time during the pulse, following a simple electronic trigger signal. This abruptness of extinguishing of the flash is uniquely characterized by zero electrical and thermal inertia (continuation of the pulse after termination) or overshoot, which exists in prior art systems due to residual inductive and / or capacitive electrical energy circulating through the load even after termination commences. Thus, an accurate pulse width is achieved, as compared with just an approximate power control to the load in prior art systems. This results in an accurate and repeatable peak front side temperature of the workpiece, a sharp maximum, and steep temporal gradients of heating just prior to termination and of conductive cooldown into the colder substrate, commencing termination. The variable pulse width capability and sharp pulse termination do not cause any damage to the various components of the system such as energy storage capacitors, flashlamps, and charging power supply. In particular, harmful over voltages, reversal of voltages, oscillations, harmonics, and excessive over currents, which generally occur in pulse modulators and generators when interrupting or rerouting suddenly the current flow, are completely eliminated. The implementation of the present invention is suitable for low voltage

applications using power semiconductor components like IGBTs, SCRs (Thyristors), or FETs, as well as for very high charging voltages and very high discharge currents, using Spark Gaps, Pseudospark or Thyratron switches.



PRIOR ART

Fig. 1

Fig. 2 $C = 235$ uf, $L_0 = 180$ uH, $V_0 = 15$ kV, $K_0 = 76$ ohm-$A^{0.5}$

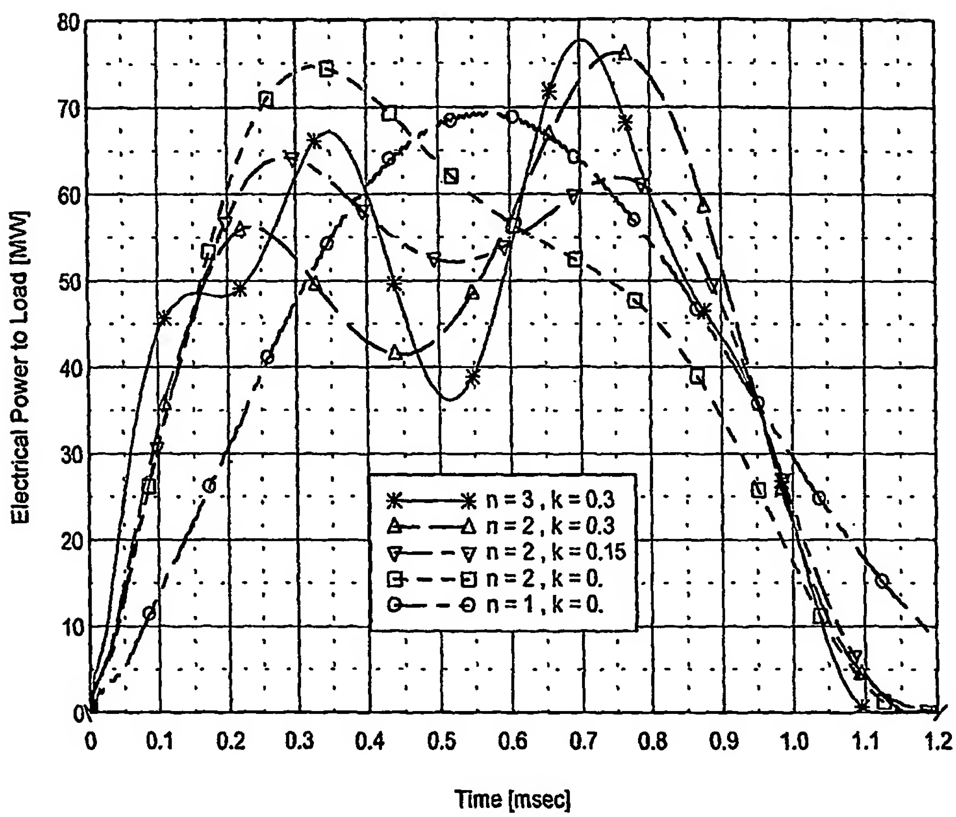
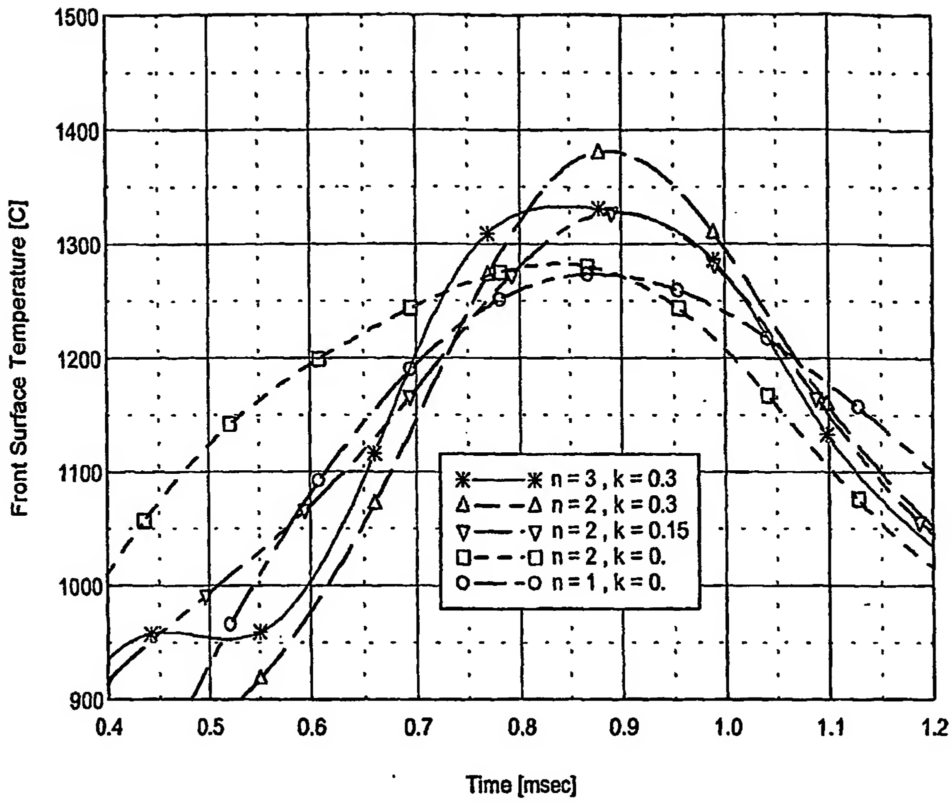


Fig.3 300mm Wafer, 4 Lamps, Database of fig.2



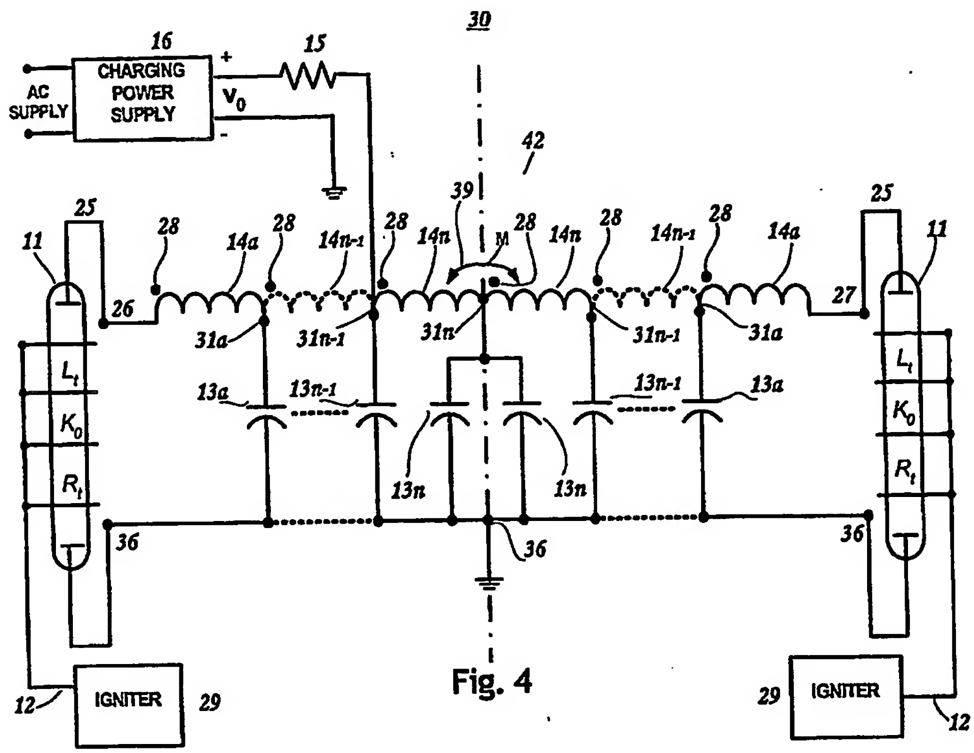

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Fig. 4

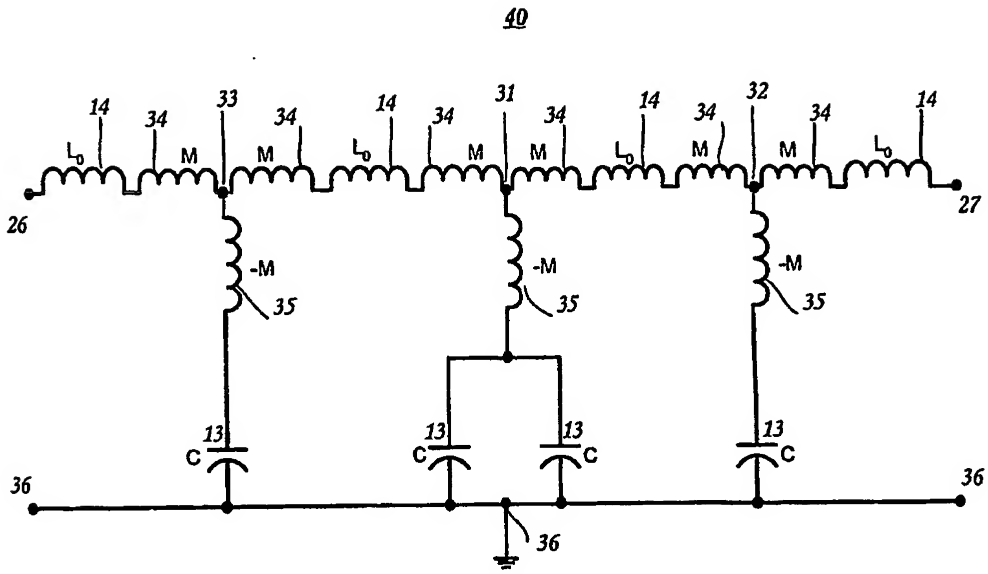
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Fig. 5

Fig. 6 Preferred Embodiment Pulse Modulator (Fig.4)

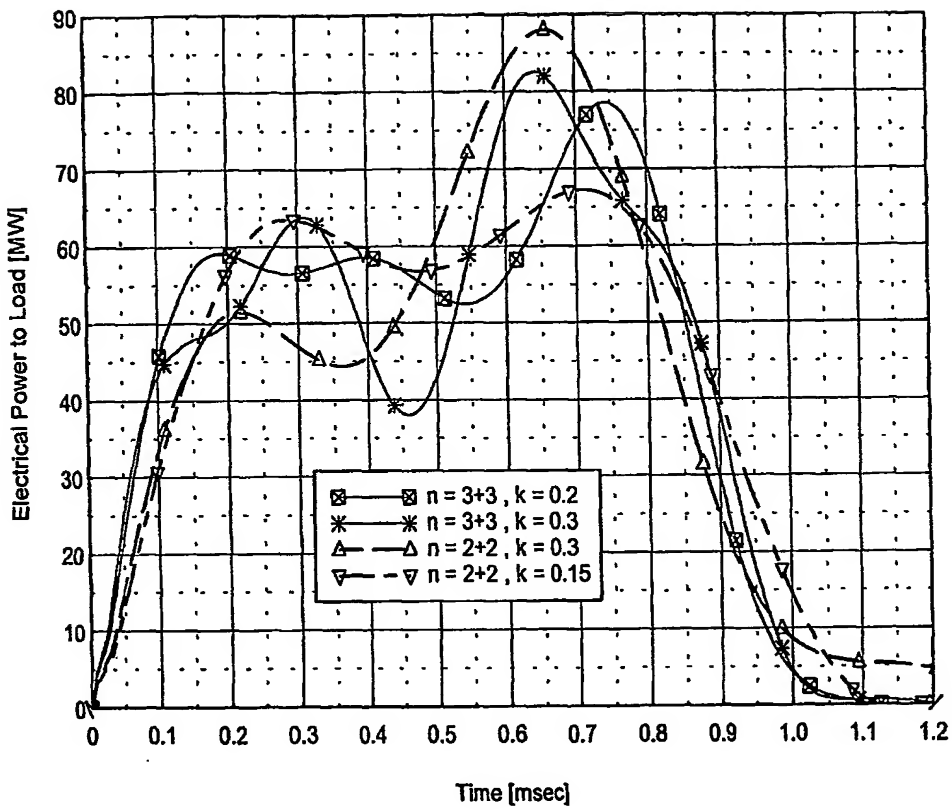
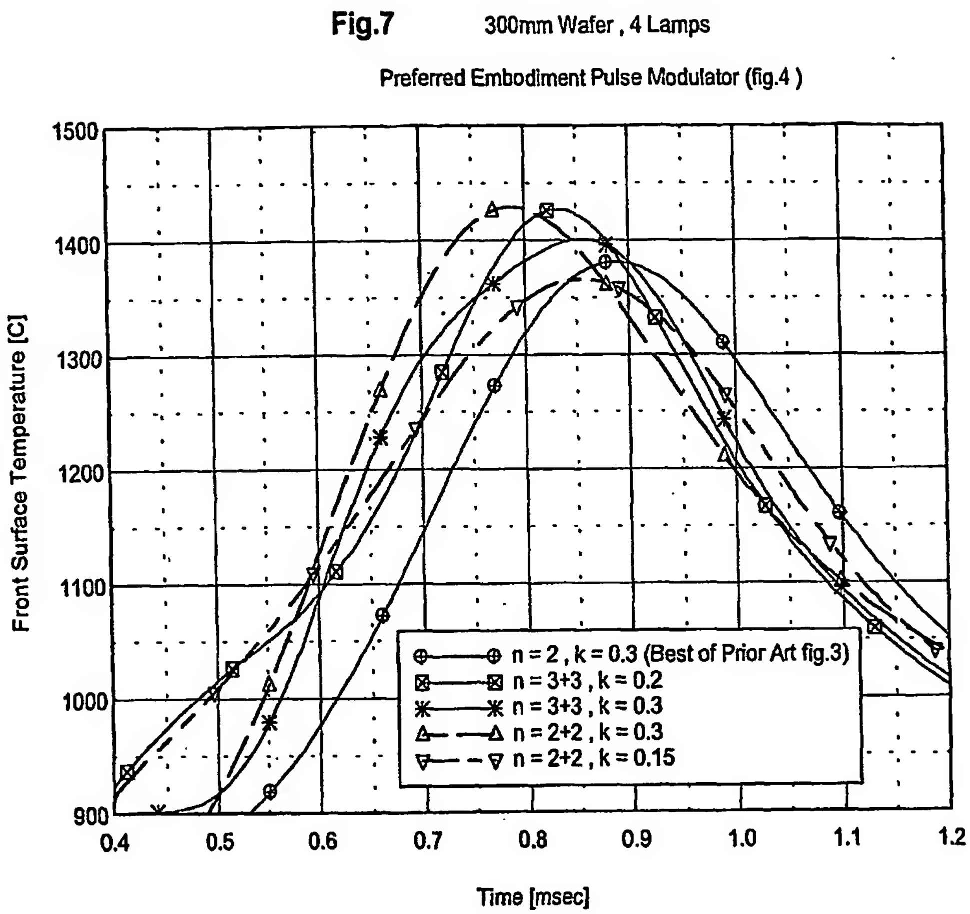


Fig.7


300mm Wafer , 4 Lamps
Preferred Embodiment Pulse Modulator (fig.4)
1500
1400
1300
1200
1100
1000
900
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
Front Surface Temperature [C]
Time [msec]
n = 2 , k = 0.3 (Best of Prior Art fig.3)
n = 3+3 , k = 0.2
n = 3+3 , k = 0.3
n = 2+2 , k = 0.3
n = 2+2 , k = 0.15

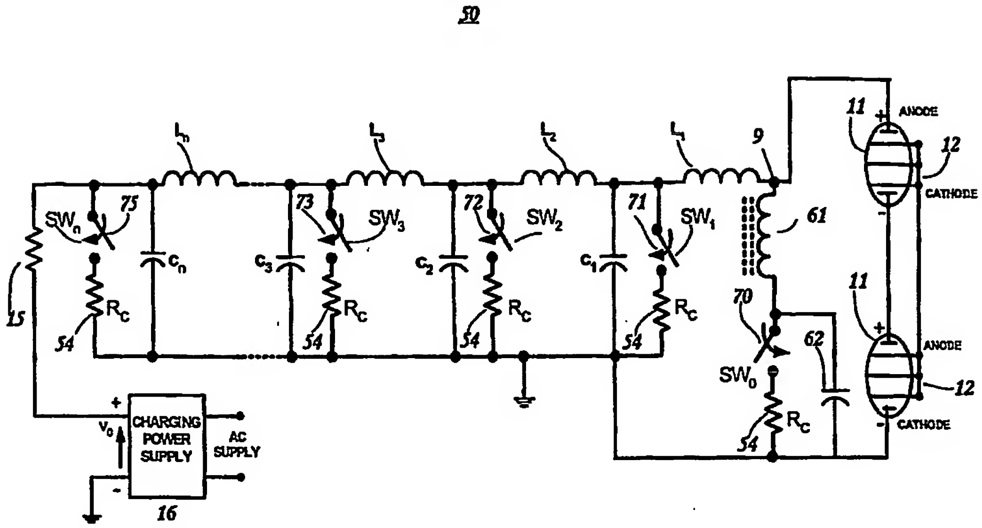
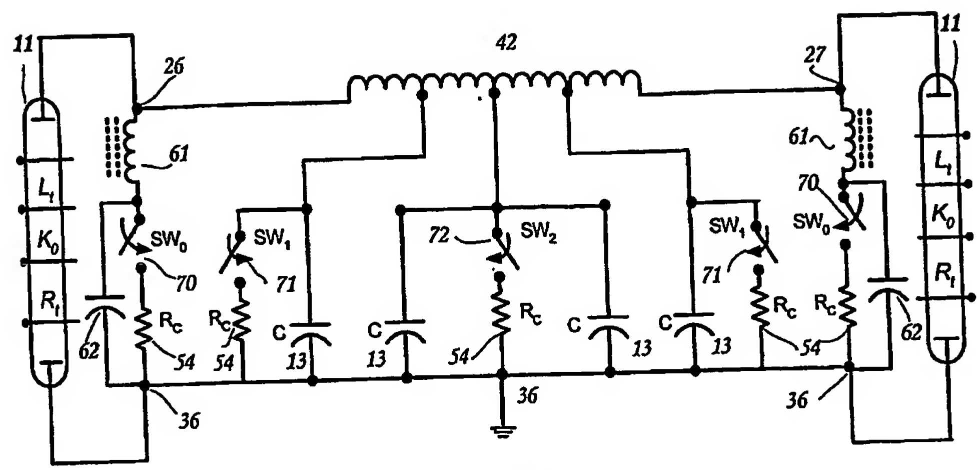

50
Ln
L3
L2
L1
9
11
ANODE
12
CATHODE
SWn
75
Cn
73
SW3
C3
72
SW2
C2
71
SW1
C1
61
Rc
15
54
70
62
SW0
ANODE
CATHODE
+
Vo
CHARGING POWER SUPPLY
AC SUPPLY
16

Fig. 8

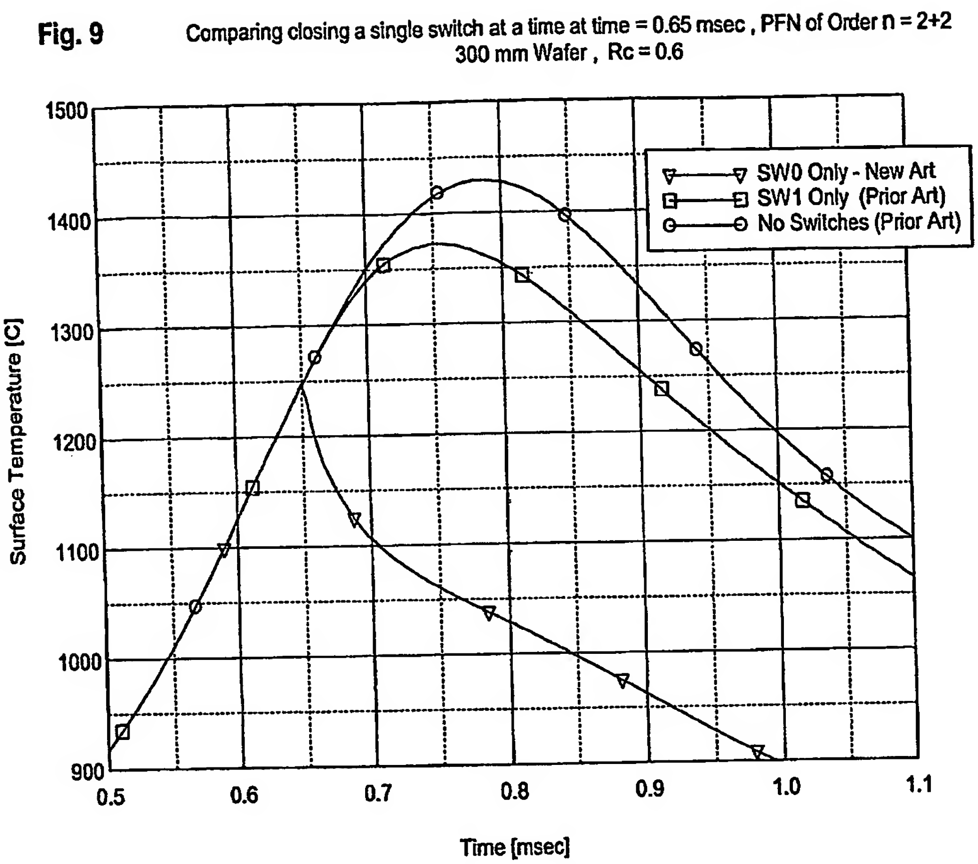
60



11
26
42
27
11
61
61
L
K
R
L
K
R
SW
SW
SW
SW
SW
70
71
72
71
70
Rc
Rc
Rc
Rc
Rc
C
C
C
C
62
54
54
13
13
54
13
13
54
62
36
36
36

Fig. 8A

Fig. 9



Comparing closing a single switch at a time at time = 0.65 msec , PFN of Order n = 2+2
300 mm Wafer , Rc = 0.6
SW0 Only - New Art
SW1 Only (Prior Art)
No Switches (Prior Art)
Surface Temperature [C]
1500
1400
1300
1200
1100
1000
900
0.5
0.6
0.7
0.8
0.9
1.0
1.1
Time [msec]

Fig. 10 Preferred Embodiment of Closing SW_0 at 0.70 & 0.75 msec, PFN of Order n = 2+2
300 mm Wafer, Rc in ohms

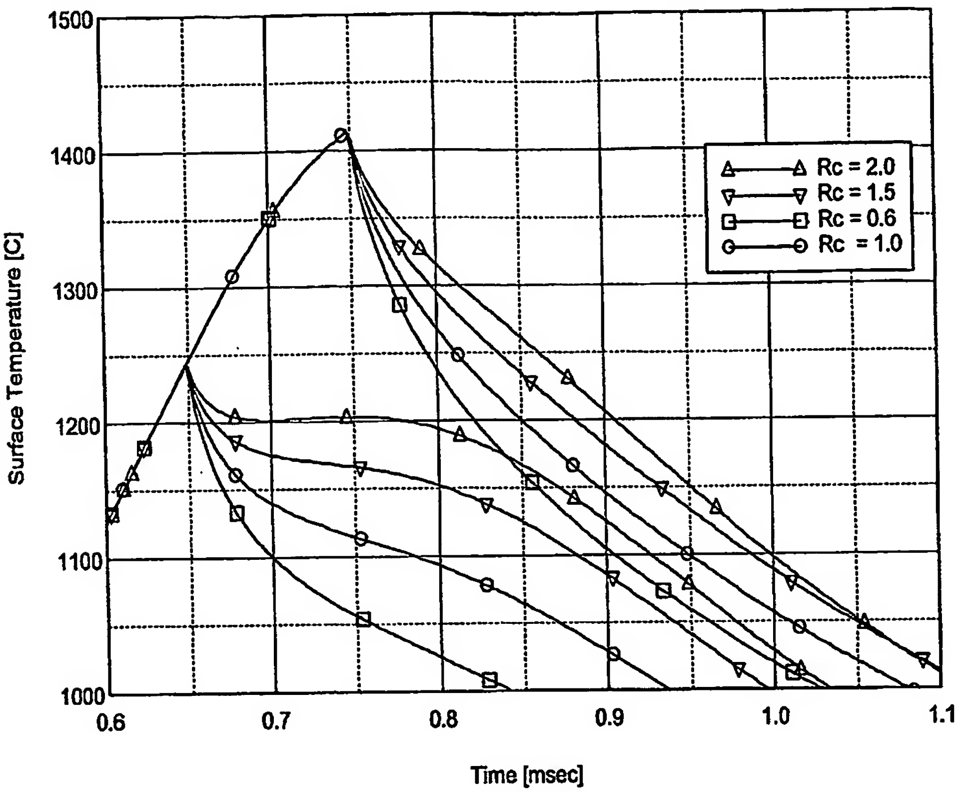


Fig.11

Termination Time = 0.65 msec, V_0 = 15 kV, PFN of Order n = 2+2
Preferred Embodiment, R_c in ohms